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The application of FLOX/COSTAIR technologies to reduce NO_x emissions from coal/biomass fired power plant: A technical assessment based on computational simulation

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Abstract

Nitrogen oxides (NO_x) is one of the harmful emissions from power plants. Efforts are made to reduce NO_x emissions by researchers and engineers all the times. NO_x emissions are from three resources during the combustion: prompt NO, fuel NO and thermal NO. The last one – thermal NO, which is described by 'Zeldovich-mechanism', is the main source for NO_x emissions. The thermal NO emission mainly results from the high combustion temperature in the combustion process. In order to control the NO formation, the control of peak combustion temperature is the key factor, as well as the oxygen concentration in the combustion areas. Flameless oxidation (FLOX) and continuous staged air combustion (COSTAIR) are two relatively new technologies to control the combustion temperature and the reaction rate and consequently to control the NO_x emissions.

In this study both FLOX and COSTAIR technologies are assessed based on a 12 MW_e, coal-fired, circulating fluidised bed combustion (CFBC) power plant by using ECLIPSE simulation software, together with a circulating fluidised bed gasification (CFBG) plus normal burner plant. Two different fuels – coal and biomass (straw) are used for the simulation. The technical results from the study show that the application of FLOX technology to the plant may reduce NO_x emissions by 90% and the application of COSTAIR technology can reduce NO_x emissions by 80–85% from the power plant. The emissions from the straw-fuelled plants are all lower than that of coal-fuelled ones although with less plant efficiencies.

Keywords: Coal power plant; Biomass; NO_x emissions; Flameless oxidation (FLOX); Continuous staged air combustion (COSTAIR)

1. Introduction

Coal is the largest energy resource in the world. It is abundant and widely available, safe, secure and affordable; easy to transport and store. The proved reserves of coal are 909,064 million tonnes including bituminous coal, anthracite coal, sub-bituminous coal and lignite in the world in 2004, which can be lasted for at least 200 years at current production rates. In the same year, the production of total world coal is 2732.1 million tonnes oil equivalent, which is more than 20% of the total primary energy supply in the year [1]. Meanwhile, more than 60% of the outputs of coal are consumed for electricity production in the world [2].

Electrical power generation from coal is a well-established and highly reliable technology. Coal produces 39%

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of the world's electricity, which is twice as much as the next largest source. Coal used in power generation is projected to grow 60% by 2030 [1]. Statistic data show that coal is still the most important energy resources in the world today and in the future.

But as a fuel, coal has its own disadvantages because it is the most carbon intensive fuel for electricity generation. The combustion of coal generates not only carbon dioxide (CO_2), but also the other harmful gases such as carbon monoxide (CO), nitrogen oxides (NO_x) and sulphur oxides (SO_x). These emissions from the coal-fired power plant are widely recognised as having a major impact on health, acidification and climate change. This poses challenges for the researchers and engineers to find out new technologies to control the emissions from these coal-based power generations.

The utilisation of renewable energy may reduce the greenhouse gas emissions. Biomass (wood, straw, grasses, etc.) is one of the most popular resources of renewable energy. It is abundant and can be found, or planted and harvested all over the world. It was the most common fuel used in the past and now it is still widely used in the third world [3]. According to the report from the Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment in 2003, the forest plantations are 186,733,000 ha and the total forest resources are 422,256 million tonnes [4], nearly half as great as the reserves of coal. The fuel wood production is 1433.7 million tonnes on average worldwide from the year of 1994–2004 [5], which are more than half that coal production. The advantage for biomass over coal is that it is renewable and it is recognised as "net zero CO_2 emission" fuel due to its very short-term carbon cycle.

From this point of view, biomass will play a more and more important role to meet the energy demand for the world. Biomass has been used in some power generation [6], but the applications are still in very limited scales/areas. The combustion of biomass generates nitrogen oxides (NO_x) and carbon monoxide (CO), although it has "zero net carbon emissions". Therefore it is necessary to carry out more investigations to find out ways to reduce the emissions of NO_x and CO, since the properties and the combustion process of biomass are quite different from coal and other fossil fuels.

The objective of this study is to investigate the feasibility of the application of FLOX/COSTAIR technology to reduce the NO_x emissions from coal/biomass fired power plants. Due to the characteristics of FLOX/COSTAIR and the biomass availability, a conventional circulating fluidised bed combustion (CFBC) power plant, sized 12 MW_e, coal-fired, is selected as a base case for comparison in the study. This size is small for coal-fired plant and the efficiency is not high, but it is a medium and suitable size for biomass fuelled power plant in practical applications, in order to reduce biomass transportation fees to the power plants. There are two advantages of the technologies make them attractive and applicable.

One is that the CFBC and CFB gasifier is suitable for any kind of biomass, e.g. straw, wood pellets/chips, grass, etc. Irregular shapes of biomass make them difficult to be burnt completely in the other firing technology such as bubbling bed/stoker. Currently, the circulating fluidised bed combustion/gasification (CFBC/CFBG) technology can burn biomass resources from all agricultural waste like orchard pruning, pomace, shells, stalks, pits, straws; from all forest-based waste like wood waste, bark and municipal waste like sludge.

Another advantage is that it can handle fuels with moisture content varying from 15% to 60%.

Two circulating fluidised bed gasification (CFBG) with integrated low NO_x gas burners power plants are proposed. One system is a CFBG with a FLOX burner, and the other a CFBG with a COSTAIR burner. In addition a CFBG with a normal burner is investigated, to compare the characteristics of the performances and emissions from these power plants. Different fuels – coal and biomass are selected for the investigation.

Seven kinds of biomass fuels such as straw, wood pellets, wood chips, etc. are used in the investigation. The performances of the system are a little different from each other for these seven different biomass fuels. The performance of the system fuelled by coal is very different compared to that fuelled by biomass. Straw is selected here to represent biomass fuel to compare with coal.

2. The technologies of flameless oxidation and continuous staged air combustion

The detailed description of the features of flameless oxidation and continuous staged air combustion are presented in the following sub-sections.

2.1. Flameless oxidation

In flameless oxidation mode [7], fuel and air are gradually mixed with large amounts of recirculated exhaust gas thereby reducing the adiabatic flame temperature of the mixture and heating up the air and fuel or air/fuel mixture at the same time. The basic principle of flameless oxidation burner is shown in Fig. 1. The main feature of flameless oxidation is: no air is added to the fuel prior to injection. The energy required for ignition is provided by the recirculating flue gas. The temperature in the furnace chamber must be at least 800–900 °C. The recirculating flue gas should be mixed into the combustion air and into the fuel, or into the fuel air mixture. The amount of the recirculating flue gas should be large enough to offer the energy to ignite the fuel air mixture. The flue gas recirculating is mainly internal recirculation, as shown in Fig. 1. This means that most of the flue gas is recirculated in the combustion chamber. For flameless oxidation, the fuel and the air are both injected directly into the furnace chamber. They react downstream from the point of injection. That leads to very low flame temperatures and low oxygen partial pressures in

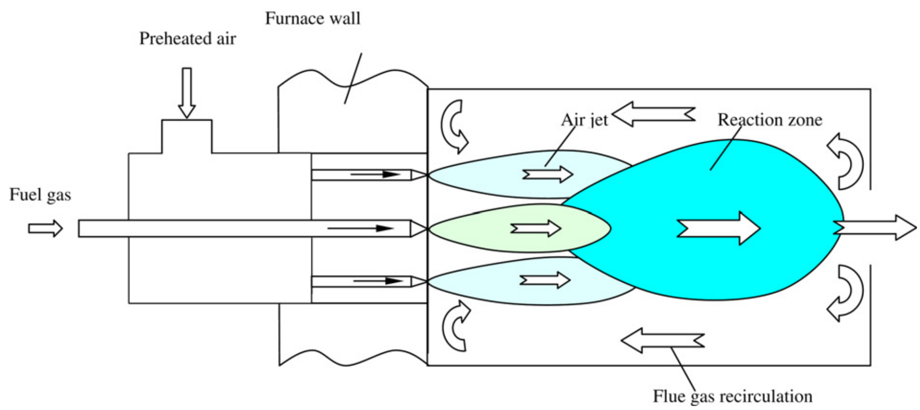

Fig. 1. Flameless oxidation burner.

the reaction zone and as a result of this to a low thermal NO formation, and then low NO_x emissions.

2.2. Continuous staged air combustion

In the mode of continuous staged air combustion [8,9], the basic principle as shown in Fig. 2, preheated air is divided into two parts, primary air and secondary air (in reality, the air can be divided into more parts depending on the application and the design), to mix with the fuel at two different points. The heat is released more uniformly throughout the combustion chamber; this results in lower NO_x formation notably. Fig. 2 shows a two-stage burner which represents the basic principle of COSTAIR. The secondary air is injected directly into the combustion chamber, flue gas is recirculated (FGR) and this enhances the NO_x reduction effect. FGR reduces NO_x by reducing the peak temperature in the burner. By diluting the charge with inert gas, the adiabatic flame temperature is reduced. This has the opposite effect of increasing oxygen availability during combustion. The recirculated gas also reduces peak combustion temperature by absorbing some of the heat of combustion. Nitrogen oxides are known to form at high temperatures and this reduction in temperature leads to decreased NO_x formation in the burner therefore leads to low NO_x emissions.

3. The power plants

A CFBC power plant is shown in Fig. 3. The detailed structure of CFBC furnace is showed in Fig. 4(1). The crushed fuel and limestone are injected into the combustor. The fuel particles are suspended in a stream of upwardly preheated flowing air, which enters the bottom of the furnace through air distribution nozzles. Secondary air is injected through a set of nozzles higher up the chamber walls. The high fluidising velocity forms an expanded bed with material carried out of the combustor. Cyclones separate the majority of the solids from the flue gas. The solids are returned either directly to the combustor or through a set of external heat exchangers which receive preheated fluidising air. The combustion takes place at 840–900 °C also helps to reduce NO_x formation. Sulphur retention is achieved by adding limestone and therefore no additional flue gas desulphurisation is required.

The steam from the superheater goes to the turbine stop valve and is expanded in the intermediate pressure turbine and the low pressure turbine. At the crossover from the intermediate to the low pressure turbines steam is extracted for the deaerator. The steam from the low pressure turbine is condensed and the condensate is pumped by the low pressure pump through the low pressure heater to the deaerator. Here the incoming water is heated by direct

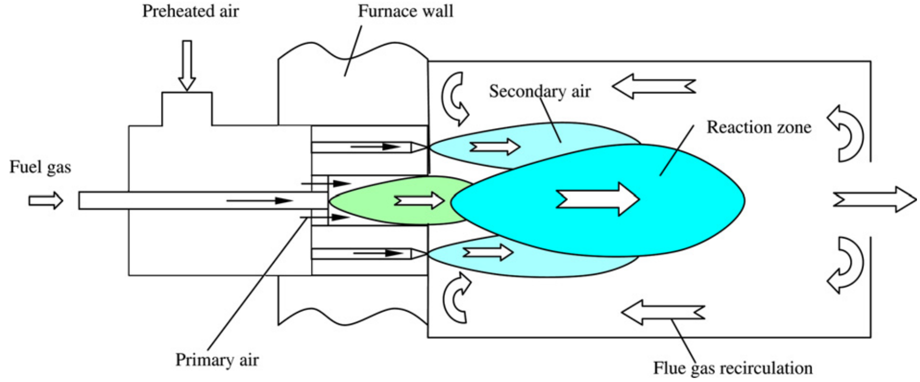

Fig. 2. Continuous staged air combustion burner.

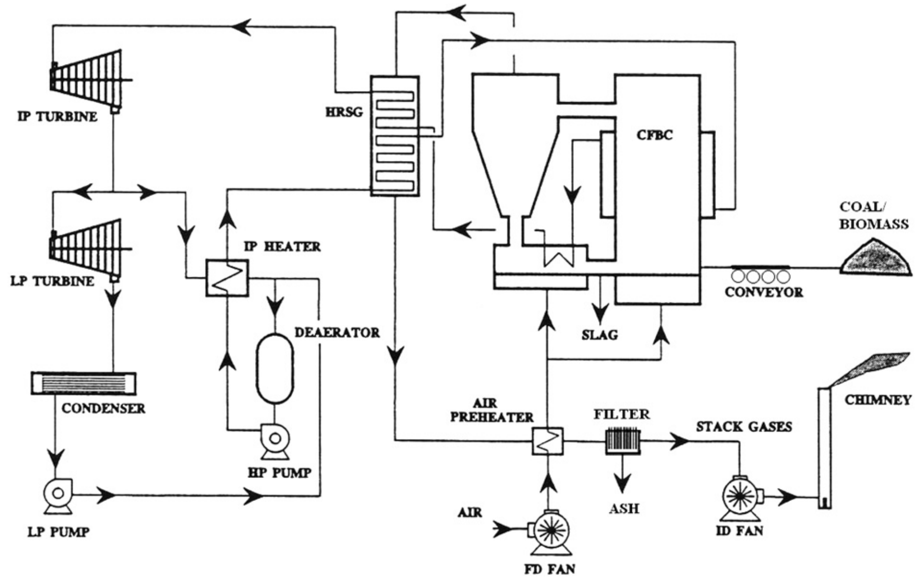

Fig. 3. CFBC power plant.

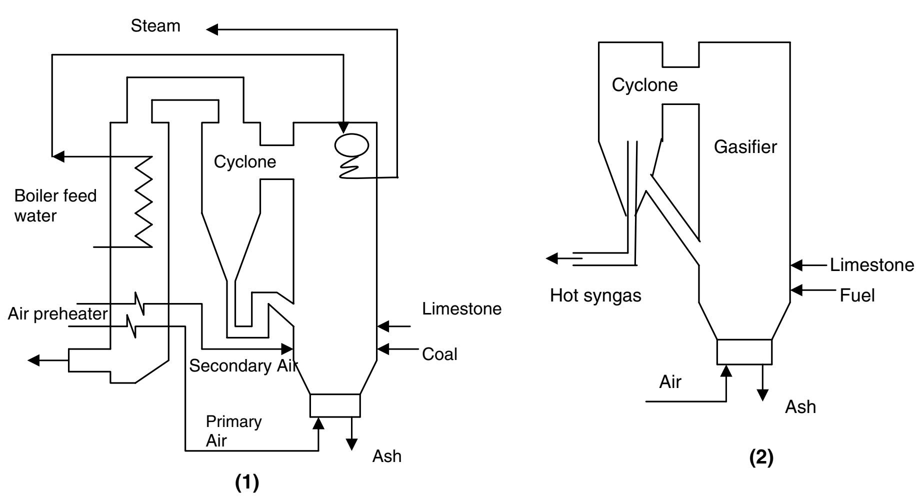

Fig. 4. The detailed structure of CFBC (1) and CFBG (2).

contact with the bleed steam. The boiler feed pump (intermediate pump) forces the condensate through economiser before reaching the boiler and completing the steam cycle.

The structure of circulating fluidised bed gasification system (CFBG) in this study is operating at atmospheric pressure, which is shown in Fig. 4(2). The system consists of a gasifier where the gasification takes place, a cyclone to separate the circulating-bed material (silica sand) from the gas, and a return pipe for returning the circulating material to the bottom part of the gasifier.

The operating temperature in the gasifier is typically 800–950 °C. Air is blown from the air fan and fed to the bottom of the gasifier. The air velocity is high enough to fluidise the fuel particles. Fuel particles are fed into the lower part in the gasifier and are pyrolysed when they are heated up. Volatiles are released and char is produced, resulting in up to 70% weight loss for fuel. This pyrolysis is fast due to the good thermal contact between fuel and the hot bed material.

The combustion process occurs as the volatile products and some of the char reacts with oxygen to form CO_2 and CO, which provides heat for the subsequent gasification reactions. The gas lifts the char and sand upwards in the gasifier. The char reacts with CO_2 and H_2O in the fuel to produce CO and H_2.

The reaction is continuing and fuel particles are converted to gases, char and tars until they reach the end of cyclone. In the cyclone residue char and sand are separated from the gas and led to the gasifier again. The hot syngas is then sent to the burner of the power plant. The ash accumulates at the bottom in the gasifier and is removed by an ash conveyer. This completes the whole cycle for the CFBG.

Silica sand is normally used as a heat carrier between the overall exothermic reactions during the gasification to the endothermic pyrolysis; and to stabilise the temperature in the process.

The hot syngas supplied to the burners (normal/FLOX/COSTAIR respectively) is burnt to generate heat for the steam cycle. In the systems studied, it is intended that the exit of the gasifier and the entrance of the burner will be in direct contact, so that any large molecules (e.g. tar) leaving the gasifier will remain in the gas phase and be burnt/cracked on entering the burner. In this case, there is no heat exchanger required for recovering the heat in syngas. The steam cycle of the CFBG system is similar to the CFBC process described above.

Due to the properties of coal and biomass are very different, different handling equipments, which are commercial available technologies, are used for these two different fuels.

The four systems assessed are shown in the following figures: (a) conventional CFBC power plant shown in Fig. 3; (b) CFBG with normal burner presented in Fig. 5; (c) CFBG with COSTAIR burner shown in Fig. 6; and (d) CFBG with FLOX burner presented in Fig. 7.

4. Simulation of the processes

In order to provide a consistent basis for evaluation and comparison, the systems analysed are modelled using the

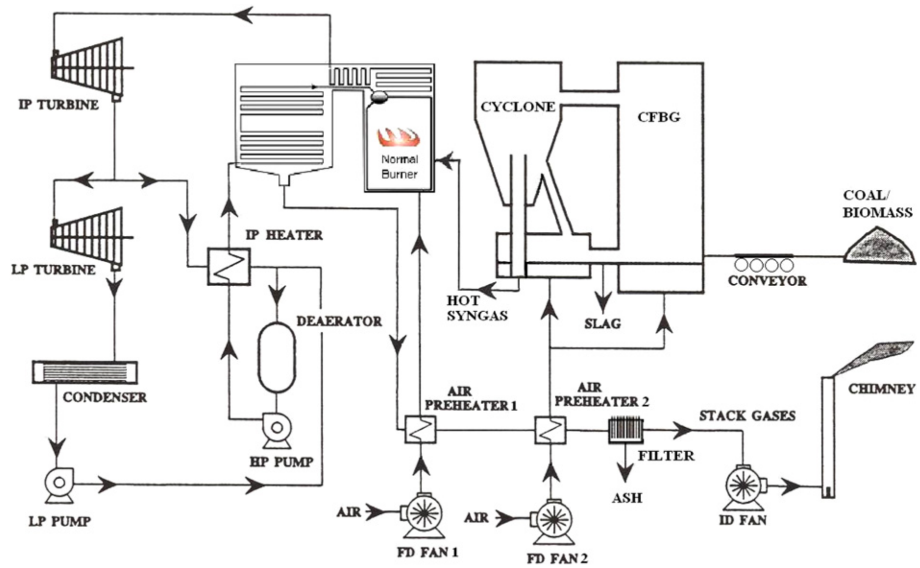

Fig. 5. CFBG + normal gas burner power plant.

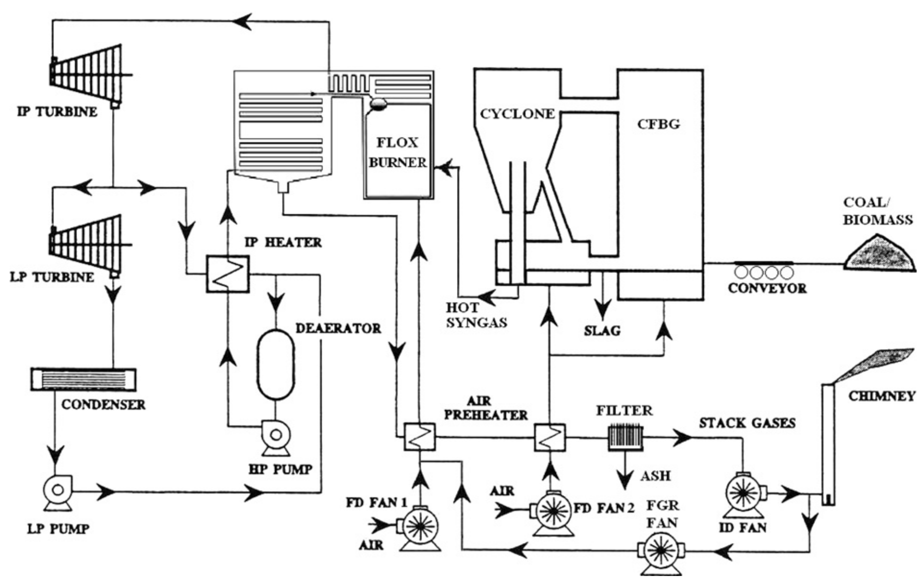

Fig. 6. CFBG + FLOX gas burner power plant.

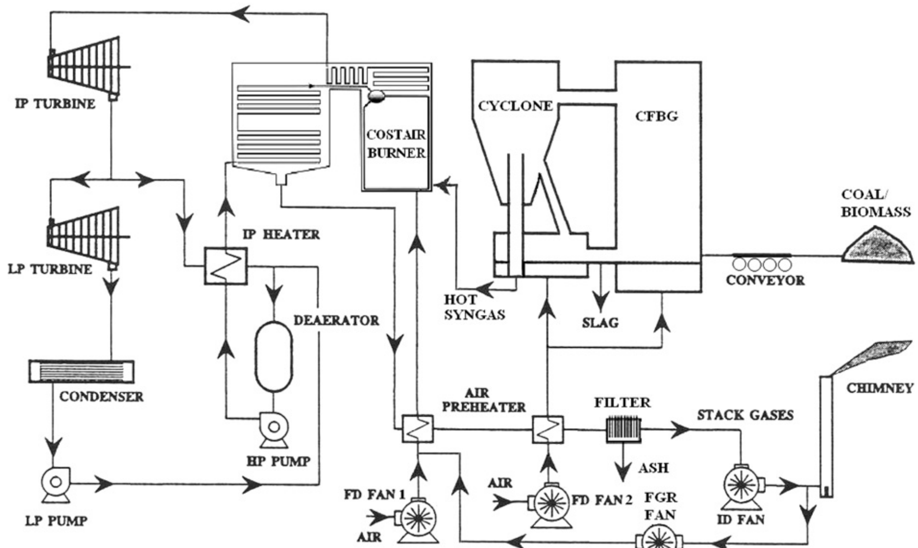

Fig. 7. CFBG + COSTAIR gas burner power plant.

ECLIPSE process simulation package [10–12]. ECLIPSE was developed for the European Commission and has been used by the Northern Ireland Centre for Energy Research and Technology at the University of Ulster since 1992 [13,14]. ECLIPSE is a personal-computer-based package containing all of the program modules necessary to complete rapid and reliable step-by-step technical, environmental and economic evaluations of chemical and allied processes.

ECLIPSE uses generic chemical engineering equations and formulae and includes a high-accuracy steam-water thermodynamics package for steam cycle analysis. It has its own chemical industry capital costing program covering over 100 equipment types. The chemical compound properties database and the plant cost database can both be modified to allow new or conceptual processes to be evaluated.

Using ECLIPSE, the technical assessment studies are carried out in stages; initially process flow diagrams are prepared, technical design data are added and the calculation of mass and energy balance are carried out. Consequently, the system's electrical generation and consumptions are calculated, environmental impact is assessed, capital and operating costs are estimated and an economic analysis performed.

In this study, only technical assessments are investigated for the four systems. The fuel properties used are listed in Table 1. The detailed analyses and results for the evaluation are presented in the following section.

Table 1
Fuel properties

Fuel	Coal	Straw
Ash (% ar)	6.22	3.2
VM and FC (% ar)	87.48	84.7
Water (% ar)	6.30	12.1
HHV (MJ/kg daf)	35.90	19.1
Carbon	84.00	47.8
Hydrogen	5.70	5.9
Nitrogen	1.50	0.5
Sulphur	2.60	0.07
Chlorine	0.14	0.00
Oxygen	6.06	42.5

5. Results and discussion

The main technical and environmental results are summarized in Table 2 for the four systems of CFBC, CFBG + normal burner, CFBG + FLOX burner and CFBG + COSTAIR burner in connection with the fuel shown in Table 1. The thermal inputs for the four power generations are all the same −43.2 MW from coal, and from biomass (straw) at lower heating value (LHV) respectively. The fuel consumptions are 110 tonnes/day (dry and ash free – daf) for coal and 216 tonnes/day (daf) for biomass (straw). The simulation of NO_x emissions is based on the results from experimental studies on the COSTAIR and FLOX burners [15,16].

When the systems are fuelled with coal, the technical performances are as following:

In case 1, in the CFBC power plant, the steam turbines generate 14.02 MW_e electricity; the auxiliaries in the process of power generation consume 1215 kW_e power; the net electricity generated is 12.81 MW_e; the thermal efficiency is 29.65% (LHV); the emissions are relative high, NO_x emissions are 249 mg/N m^3 and CO is 76 mg/N m^3; although the emissions are in the range of the data in literature [17,18] and within the limits of European NO_x emission regulations [19].

In case 2, in the power plant of CFBG + normal burner, the steam turbines generate 13.96 MW_e electricity; the auxiliaries in the process of power generation consume

Table 2
Technical-mass and energy simulation results

	CFBC		CFBG + normal gas burner		CFBG + FLOX gas burner		CFBG + COSTAIR gas burner	
	Coal	Straw	Coal	Straw	Coal	Straw	Coal	Straw
Fuel input (tonnes/day) (daf)	110	216	110	216	110	216	110	216
Fuel moisture content (%)	6.30	12.1	6.30	12.1	6.30	12.1	6.30	12.1
FD Fan (kW_e)	495	496	495	501	1299	888	1317	888
ID Fan (kW_e)	74	80	75	81	115	127	118	127
Ash box (kW_e)	13	16.2	13	16.2	13	16.2	13	16.2
Gas cleaning (kW_e)	0.7	0.9	0.7	0.9	0.7	0.8	0.7	0.9
Abs convey (kW_e)	37	0	37	0	37	0	37	0
Fuel convey (kW_e)	106	155	106	155	106	155	106	155
Ash convey (kW_e)	39	14	39	14	36	16	39	14
HP pump (kW_e)	215	206	215	205	217	205	217	205
LP pump (kW_e)	1.6	1.5	1.6	1.5	1.6	1.5	1.6	1.5
Total (kW_e)	982	970	982	975	1826	1410	1850	1408
IP turbine (kW_e)	6717	6426	6698	6391	6785	6412	6784	6406
LP turbine (kW_e)	7305	7261	7266	7202	7375	7224	7375	7217
Electric process (kW_e)	14,022	12,717	13,963	12,618	14,160	12,226	14,159	12,215
Electric utility (kW_e)	233	231	231	229	235	230	235	230
Net electric (MW_e)	12.81	12.49	12.75	12.39	12.10	12.00	12.07	11.98
Steam cycle (bar/°C)	80/480	80/480	80/480	80/480	80/480	80/480	80/480	80/480
Thermal input LHV (MW)	43.2	43.2	43.2	43.2	43.2	43.2	43.2	43.2
Thermal input HHV (MW)	45.2	47.4	45.2	47.4	45.2	47.4	45.2	47.4
Efficiency LHV (%)	29.65	28.93	29.51	28.71	28.01	27.80	27.95	27.77
Efficiency HHV (%)	28.32	26.36	28.20	26.15	26.76	25.33	26.70	25.30
Exhaust gas temperature (°C)	123	123	123	123	126	131	127	131
Exhaust gas flow (kg/s)	20.42	21.82	20.54	22.01	20.54	22.01	20.54	22.01
CO_2 (g/kW h)	1134	1295	1112	1297	1172	1339	1174	1341
SO_2 (mg/N m^3)	300	209	288	207	288	207	288	207
CO (mg/N m^3)	76	51	79	50	37	30	37	30
NO_x (mg/N m^3)	249	211	251	210	25	21	50	31
HCl (mg/N m^3)	112	0	113	0	113	0	113	0
O_2 (dry) (vol%)	5.59	5.47	5.62	5.31	5.63	5.32	5.63	5.32

1213 kW_e power; the net electricity generated is 12.75 MW_e; the thermal efficiency is 29.51% (LHV), which is almost the same as that of CFBC; the emissions are also similar to that of CFBC, the NO_x emissions are 251 mg/N m^3, the CO emission is 79 mg/N m^3.

In case 3, in the plant of CFBG + FLOX burner, the steam turbines generate 14.16 MW_e electricity; the auxiliaries in the process of power generation consume 2061 kW_e power. More power used in the process is due to the power consumed for the flue gas recycle (FGR) pump in the system. The net electricity generated is 12.10 MW_e; the thermal efficiency is 28.01% (LHV), which is 5.53% lower than that of CFBC; but the emissions are much lower compared with that of CFBC (also CFBG + normal burner), NO_x emissions are 25 mg/N m^3, the reduction is 90%; CO emission is 37 mg/N m^3, the reduction is 50%.

In case 4, in the plant of CFBG + COSTAIR burner, the steam turbines generate 14.16 MW_e electricity; the auxiliaries in the process of power generation consume 2085 kW_e power. Net electricity generated is 12.07 MW_e; the thermal efficiency is 27.95% (LHV), which is 5.73% lower than that of CFBC; but emissions are much lower. NO_x emissions are 50 mg/N m^3, the reduction is 80% compared with that of CFBC; CO emission is 37 mg/N m^3, the reduction is 50%.

When the systems are fuelled with biomass (straw), compared with that fuelled with coal in the same plant technology, the technical performances are as following:

In case 1 of CFBC, the steam turbines generate 12.72 MW_e electricity; the auxiliaries in the process of power generation consume 1201 kW_e power; the net electricity generated is 12.49 MW_e, which is lower than that fuelled with coal; the thermal efficiency is 28.93% (LHV), which is 2.43% lower; NO_x emissions are 211 mg/N m^3 and CO is 51 mg/N m^3, which are 15% and 33% lower respectively.

In case 2 of CFBG plus normal burner, the steam turbines generate 12.62 MW_e electricity; the auxiliaries in the process of power generation consume 1204 kW_e power; the net electricity generated is 12.39 MW_e; the thermal efficiency is 28.71% (LHV), which is 2.71% lower; NO_x emissions are 210 mg/N m^3, CO emission is 50 mg/N m^3, which are 16% and 37% lower respectively.

In case 3 of CFBG plus FLOX, the steam turbines generate 12.23 MW_e electricity; the auxiliaries in the process of power generation consume 1640 kW_e power. The net electricity generated is 12.00 MW_e; the thermal efficiency is 27.80% (LHV), which is 0.75% lower; NO_x emissions are 21 mg/N m^3, the reduction is 16%; CO emission is 30 mg/N m^3, the reduction is 19%.

In case 4 of CFBG plus COSTAIR, the steam turbines generate 12.22 MW_e electricity; the auxiliaries in the process of power generation consume 1638 kW_e power. Net electricity generated is 11.98 MW_e; thermal efficiency is 27.77% (LHV), which is 0.64% lower than that fuelled with coal; NO_x emissions are 31 mg/N m^3, the reduction is 38%; CO emission is 30 mg/N m^3, the reduction is 19%.

6. Conclusions

The above assessment of alternative NO_x reduction technologies to the CFBC coal-fired power plant was successfully completed using the ECLIPSE process simulator.

Compared to the conventional CFBC coal-fired power plant, the NO_x emissions are reduced by 90% using FLOX burner and are reduced by 80% using a COSTAIR burner.

With the same thermal inputs (LHV 43.2 MW) from coal, the electricity outputs are 12.81, 12.75, 12.10, 12.07 MW_e and the electrical efficiencies are 29.65%, 29.51%, 28.01%, 27.95% for the four plants. The reduction of the electrical outputs are due to the power consumption by the FD fan and ID fan for the flue gas recirculation in FLOX and COSTAIR cases.

With the same thermal inputs (LHV 43.2 MW) from biomass (straw), the electricity outputs are 12.49, 12.39, 12.00, 11.98 MW_e and the electrical efficiencies are 28.93%, 28.71%, 27.80%, 27.77% for the four plants. They are all a little lower than that of the same plants fuelled with coal. But the NO_x and CO emissions are all lower. The distinct advantage for the power plants fuelled with biomass (straw) is that the CO_2 emissions can be treated as net zero emissions, due to its biological recycle.

The results of the technical analyses show that the use of FLOX/COSTAIR burners are able to reduce NO_x emissions dramatically; and the FLOX burner would reduce NO_x emissions more effectively than employing the COSTAIR burner, and with less of an efficiency penalty.

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References

[1] World Coal Institute, The role of coal as an energy source, 2005. http://www.worldcoal.org/assets_cm/files/PDF/role_of_coal_as_an_energy_source.pdf.

[2] International Energy Agency, World coal market 2003. http://www.iea.org/Textbase/nppdf/free/2004/coal2004_selection.pdf.

[3] Parikka M. Global biomass fuel resources. Biomass Bioenergy 2004;27:613–20.

[4] Food and Agriculture Organization of the United Nations, State of the World's Forests, 2003. http://www.fao.org/DOCREP/005/Y7581E/Y7581E00.HTM.

[5] Forests, grasslands and drylands – forest (fuel) production: wood fuel, World Resources Institute. http://earthtrends.wri.org/.

[6] Alakangas E, Vesterinen P. Biomass survey in Europe (summary report). European Bioenergy Networks, 2003.

[7] Wünning JG. Flameless combustion in the thermal process technology. In: Second international seminar on high temperature combustion in Stockholm – Sweden, January 17–18, 2000.

[8] Flamme M. New combustion systems for gas turbines (NGT). Appl Therm Eng 2004;24(11–12):1551–9.

[9] Flamme M. Low NO_x combustion technologies for high temperature applications. Energy Convers Manage 2001;42:1919–35.

[10] Williams BC. The development of the ECLIPSE simulator and its application to the techno-economic assessment of clean fossil fuel power generation systems, DPhil thesis, Energy Research Centre, University of Ulster, Coleraine, N.I., 1994.

[11] McMullan JT, Williams BC. Development of computer models for the simulation of coal liquefaction processes. Int J Energy Res 1994;18(2):117–22.

[12] Williams BC, McMullan JT. Techno-economic analysis of fuel conversion and power generation systems – the development of a portable chemical process simulator with capital cost and economic analysis capabilities. Int J Energy Res 1996;20(2):125–42.

[13] Willams BC, McMullan JT. In: Imariso B, editor. Progress in synthetic fuels. London: Graham and Trotman; 1988. p. 183–9.

[14] ECLIPSE Process Simulator, Energy Research Centre, Jordanstown, N.I., University of Ulster, 1992.

[15] Flamme M. Low NO_x combustion technologies for high temperature applications. Energy Convers Manage 2001;42:1919–35.

[16] Flamme M. New Opportunities for improvement of energy efficiency in process technology. Gaswärme-Institut e.V. Essen, Germany, 2000. www.metallurgi.kth.se/htc/skiva/presentations/flamme.pdf.

[17] IEA (International Energy Agency) Clean Coal Centre, Developments in fluidised bed combustion technology, June 2006, PF06-03. http://www.iea-coal.org.uk/publishor/system/component_view.asp?LogDocId=81456.

[18] Li Zhiwei, Lu Qinggang, Na Yongjie. N_2O and NO emissions from co-firing MSW with coals in pilot scale CFBC. Fuel Process Technol 2004;85(14):1539–49.

[19] European Communities, Directive 2001/80/EC of the European Parliament and of the Council of 23 October 2001 on the limitation of emissions of certain pollutants into the air from large combustion plants. Official J Eur Commun 2001:L309/1–L309/21.